BEAM COLLIMATION AT HADRON COLLIDERS

Nikolai Mokhov
Fermilab

HALO'03 Workshop

Montauk, May 20, 2003

OUTLINE

- Introduction
- Purpose of Collimation
- Collimation of TeV Beams: One-stage and Two-stage
- Design Constraints
- Tevatron: Present and Future
- HERA: *ep* World
- LHC: Beam Cleaning, IR and Beam Accident Challenges
- VLHC: Back to the Future

INTRODUCTION

At hadron colliders, as at any other accelerator, the creation of beam halo is unavoidable. This happens because of beam-gas interactions, intra-beam scattering, proton-proton (antiproton) collisions in the interaction regions (IP), and particle diffusion due to RF noise, ground motion and resonances excited by the accelerator magnet nonlinearities and power supplies ripple. As a result of halo interactions with limiting apertures, hadronic and electromagnetic showers are induced in accelerator and detector components causing numerous deleterious effects ranging from minor to severe. An accidental beam loss caused by an unsynchronized abort launched at abort system malfunction, can cause catastrophic damage to the collider equipment. Only with a very efficient beam collimation system can one reduce uncontrolled beam losses in the machine to an allowable level.

PURPOSE OF COLLIMATION

Beam collimation is mandatory at any superconducting hadron collider to protect components against excessive irradiation, minimize backgrounds in the experiments, maintain operational reliability over the life of the machine (quench stability among other things), and reduce the impact of radiation on environment. It provides:

1. Reduction of beam loss in the vicinity of IPs to sustain favorable experimental conditions during the whole store.
2. Minimization of radiation impact on personnel and environment by localizing beam loss in the predetermined regions and using appropriate shielding in these regions.
3. Protection of accelerator components against irradiation caused by operational beam loss and enhancement of reliability of the machine.
4. Prevention of quenching of SC magnets and protection of other machine components from unpredictable abort and injection kicker prefires/misfires and unsynchronized abort.

TEV COLLIMATION: FIRST EXPERIENCE

The most direct way of collimating a beam of particles is to define the physical aperture with a solid block of absorbing material. In the early Tevatron days the first collimation system was designed on the basis of the MARS-STRUCT simulations of beam loss formation in the machine [Drozhdin, Harrison, Mokhov (1985)]. The optimized system, consisted of a set of collimators about 1 m long each, was installed in the Tevatron which immediately made it possible to raise **by a factor of 5** the efficiency of the fast resonant extraction system and intensity of the extracted 800 GeV proton beam. The data on beam loss rates and on their dependence on the collimator jaw positions were in excellent agreement with the calculational predictions.

SCRAPING RATE IN TEV COLLIDER (1)

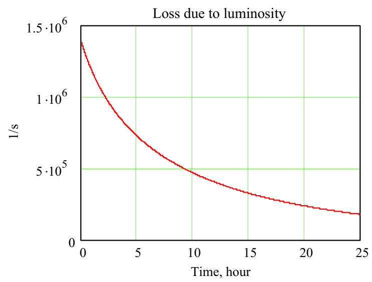
The ultimate Tevatron Run II parameters include 36 bunches of 2.7×10^{11} protons and 1.35×10^{11} antiprotons each, with normalized horizontal emittances of 20 mm-mrad and 15 mm-mrad, respectively. The total beam intensities at the beginning of the store are $N_p = 9.72\times10^{12}$ and $N_{\overline{p}} = 4.86\times10^{12}$. The ultimate luminosity at the beginning of the store would be 3.31×10^{32} cm^{-2}s^{-1} averaging to 1.43×10^{32} cm^{-2}s^{-1} over a 13.5-hour store. Next slide shows estimated evolution of beam loss over such a store for three major components:

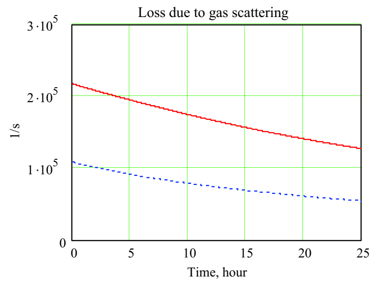
1. $\overline{p}p$ collisions at two IPs (*collision loss*), $\Delta I = 2.2\times10^7$ p/s or $\overline{p}$/s.

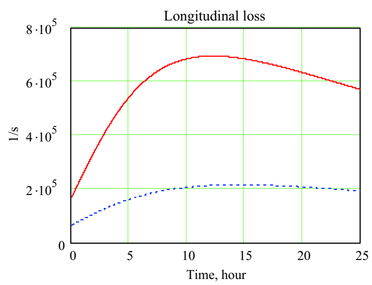
2. Particle loss from the RF bucket due to heating of a longitudinal degree of freedom (*longitudinal loss*), $\Delta I = 2\times10^7$ p/s and 6.1×10^6 $\overline{p}$/s.

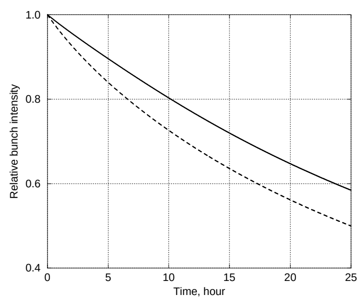
3. *Beam-gas scattering*, $\Delta I = 6.5\times10^6$ p/s and 2.9×10^6 $\overline{p}$/s, calculated at a nitrogen equivalent pressure of 10^{-9} torr with the following gas content (in nanotorr): H_2 (5.7), CO (0.14), N_2 (0.07), C_2H_2 (0.06), CH_4 (0.11), CO_2(0.07), Ar (0.09).

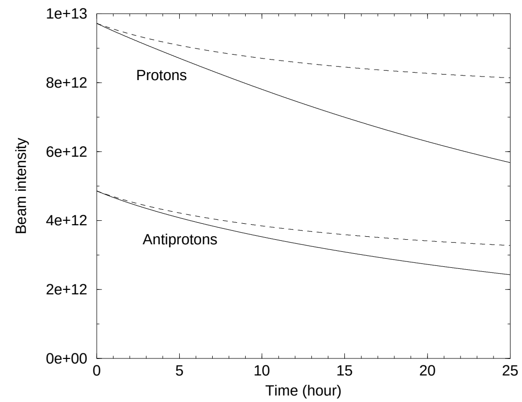
SCRAPING RATE IN TEV COLLIDER (2)











Evolution of proton (solid curves) and antiproton (dashed curves) bunch loss rates – collision (left top), longitudinal (left bottom) and beam-gas (center top) – and relative bunch intensity as evolved in a store (center bottom). Right: Proton and antiproton beam intensity evolution over a store. Dashed curves show intensity behavior with collision loss only.

SCRAPING RATE IN TEV COLLIDER (3)

Inelastic and 60% of elastic events contribute to *collision loss*, because about 40% of protons (antiprotons) elastically scattered at the Tevatron IPs remain in the 3σ core after a bunch-bunch collision. Intensity drops over a 13.5-hour store are 26% and 34% for proton and antiproton beams, respectively. Longitudinal beam loss, beam gas-scattering and elastic part of collision loss are the main mechanisms of the **slow beam halo growth**. The main collimation system is designed to intercept about 99.9% of this halo, with $N_{sp} = 2.93\times10^7$ p/s and $N_{s\bar{p}} = 1.15\times10^7$ $\bar{p}$/s as the scraping rates for proton and antiproton beams, correspondingly.

TEV COLLIMATION DIFFICULTIES

Depending upon the energy, material and thickness, a certain fraction of the intercepted beam will survive, either be traversing the whole length of the block or by being scattered out of the block. The first component can be reduced by using a longer sraper or a denser material. Suppression of the outscattered particles is much more difficult. For a given material, their yield depends upon the impact parameter Δ and particle energy. Δ grows linearly with the halo transverse diffusion velosity *v*. At Tevatron, *v* is about 1.5 μm/s and Δ = 0.1-0.5 μm. This results in a probability of outscattering close to 0.5 (low collimation efficiency), a high energy deposition density in the scraper and alignement problems.

Therefore, switch to **TWO-STAGE COLLIMATION**, with a thickness of a primary collimator (scatterer) going down to a fraction of a radiation length.

TEV TWO-STAGE COLLIMATION HISTORY

- 3 TeV UNK (Protvino) [Drozhdin, Maslov, Mokhov (1987)].
- 20 TeV SSC (Texas) [Maslov, Mokhov, Yazynin (1991)].
- 7 TeV LHC (CERN) [Burnod, Jeanneret (1991), refined in 1995].
- 0.9 TeV HERA (DESY) [Seidel (1993)].
- 1 TeV Tevatron (Fermilab) [Drozhdin, Mokhov (1995) installed, redesigned for Run-II in 1999].

TWO-STAGE COLLIMATION OF TEV BEAMS

The whole system consists of a primary *thin scattering target*, followed by a few *secondary collimators* (scrapers) at the appropriate locations in the lattice. The purpose of a thin target is to increase amplitude of the betatron oscillations of the halo particles and thus to increase their impact parameter on the scraper face on the next turns.

At Tevatron, Δ = 0.1-0.5 μm $\rightarrow$ 0.1-0.3 mm.

This results in a significant decrease of the outscattered proton yield and total beam loss in the accelerator, scraper jaws overheating and mitigating requirements to scraper alignment. Besides that, the scraper efficiency becomes almost independent of accelerator tuning, there is only one significant but totally controllable restriction of accelerator aperture and only the scraper region needs heavy shielding and probably a dogleg structure.

TWO-STAGE AT TEVATRON (1995)

In 1995, based on the MARS-STRUCT simulations, the existing scraper in Tevatron at AØ was replaced with a new one with two 2.5 mm thick L-shaped tungsten targets with 0.3 mm offset relative to the beam surface on the either end of the scraper (to eliminate the misalignment problem), resulting in reduction of beam loss rate upstream of both collider detectors by **a factor of 5** in agreement with the modeling predictions.

A TEV BEAM SYSTEM

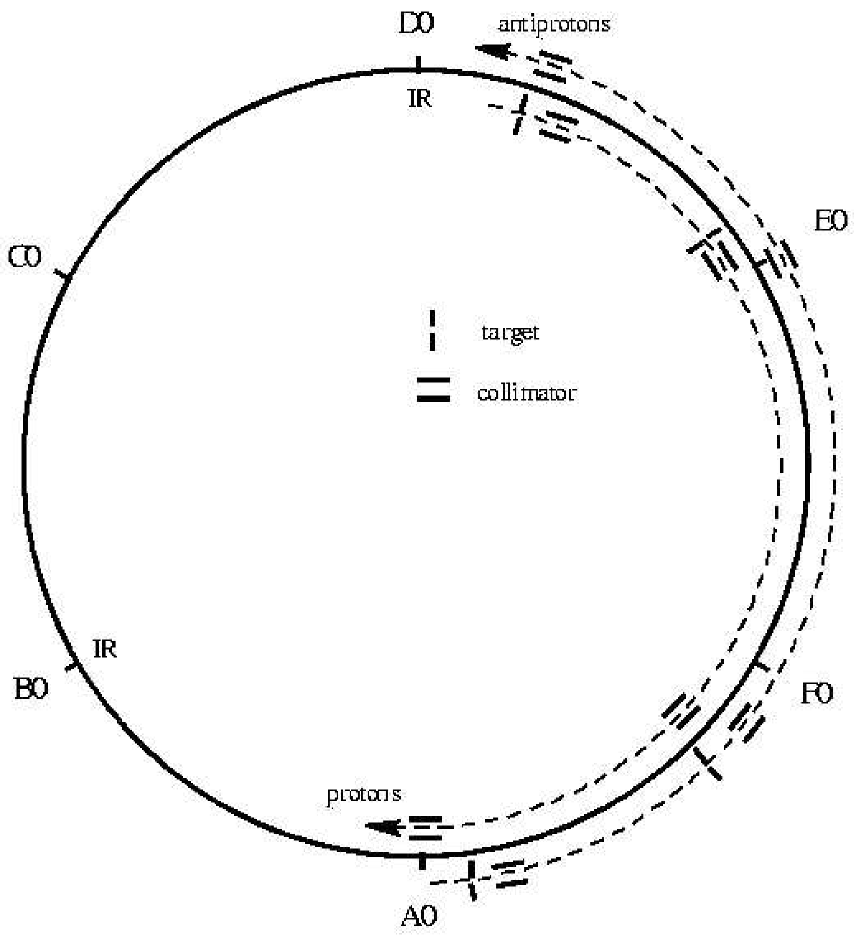
- Thin movable primary collimators (*scatteres*, *targets*, *blades*) are optimized for the beam and heating (scattering, inegrity and cooling) and positioned at 5 to 6σ from the beam axis in a high-β (*betatron cleaning*) and non-zero dispersion (*momentum cleaning*) regions $\longrightarrow$ three targets (H, V and off-momentum).

- About 1.5-m long SS adjustable H&V secondary collimators (e.g., L-shape jaws) located at the appropriate phase advances 1σ farther from the beam axis, alligned parallel to the envelope of the circulating beam.

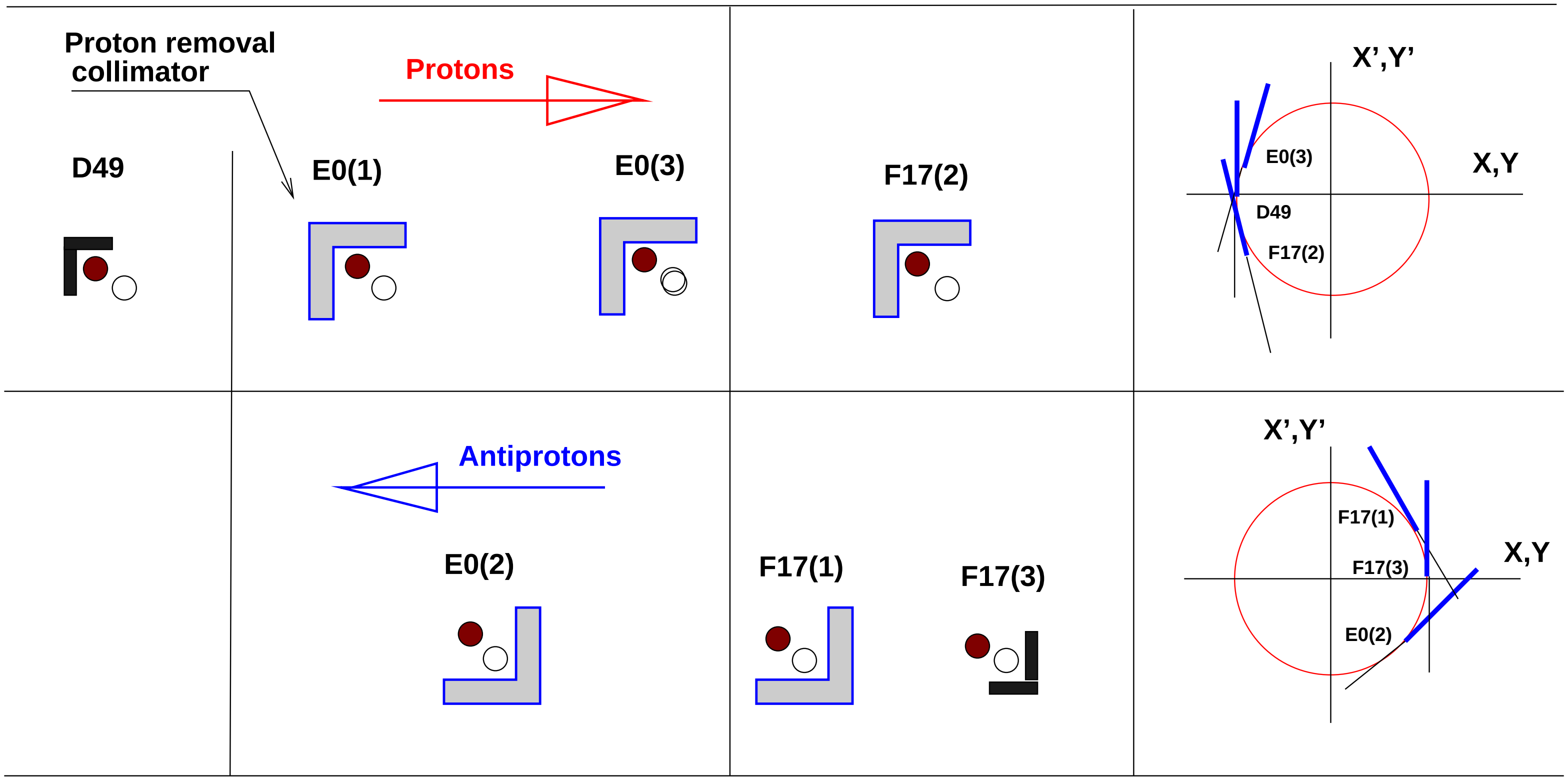
DESIGN CONSTRAINTS

- Minimum outscattering from a primary-secondary couple.
- No quench of downstream superconducting magnets.
- The apertures do not occlude any beam when in the garage position.
- Muon vectors downstream do not create any problem to the experiments and environment.
- Local shielding (if needed) provides protection of groundwater and equipment around the unit, and residual dose rate on its outside below 1 mSv/hr.
- Target/jaw material integrity and cooling issues.
- Alignement issues.
- Many other engineering constraints.

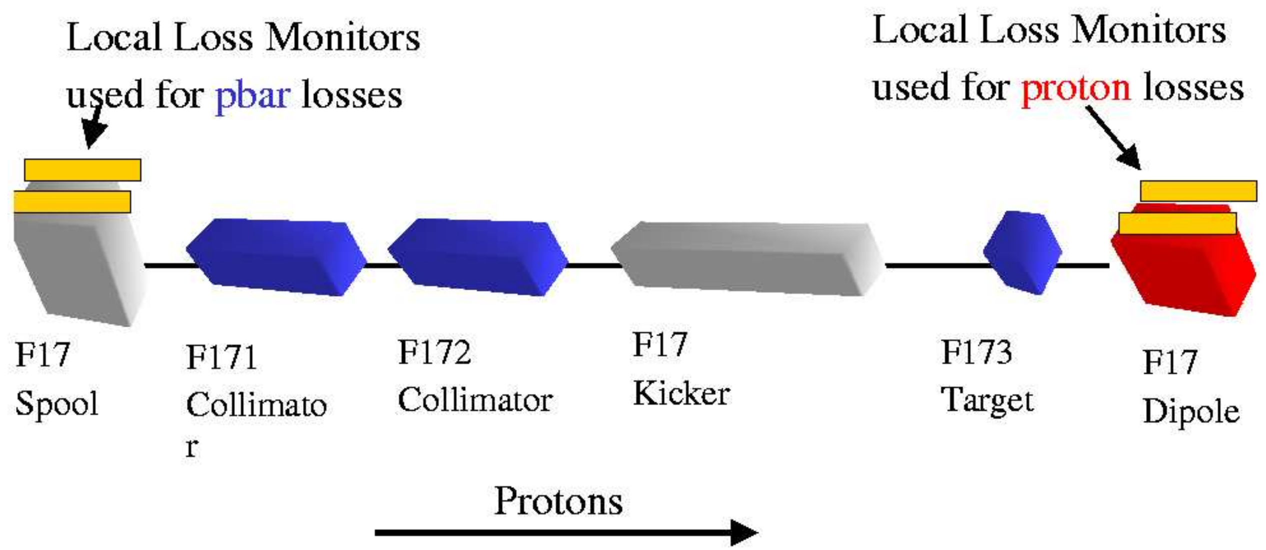
TEVATRON RUN II (1)



TEVATRON RUN II (2)



TEVATRON RUN II (3)

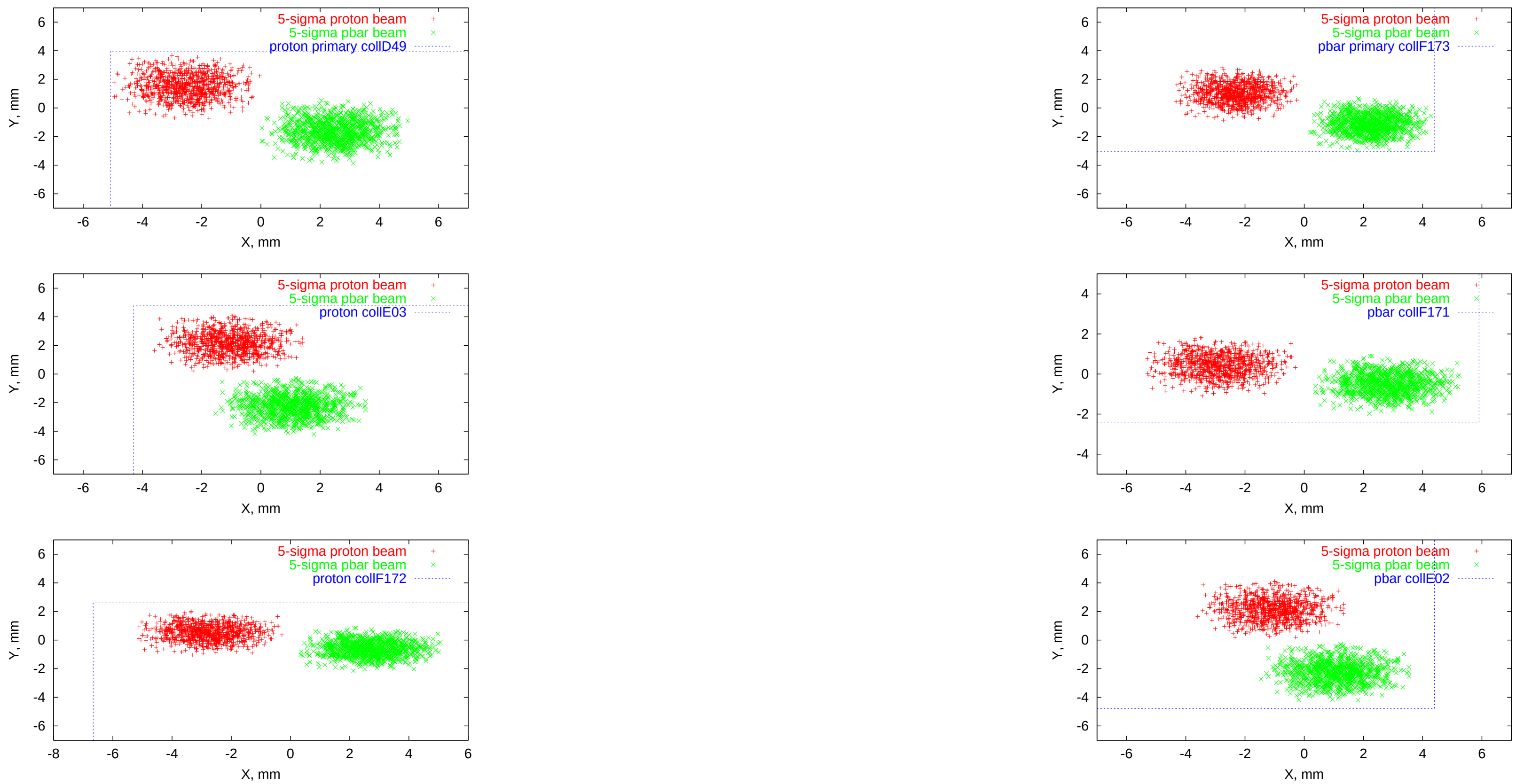


TEVATRON RUN II (4)

β-functions, dispersions and phase advances between primary and secondary collimators.

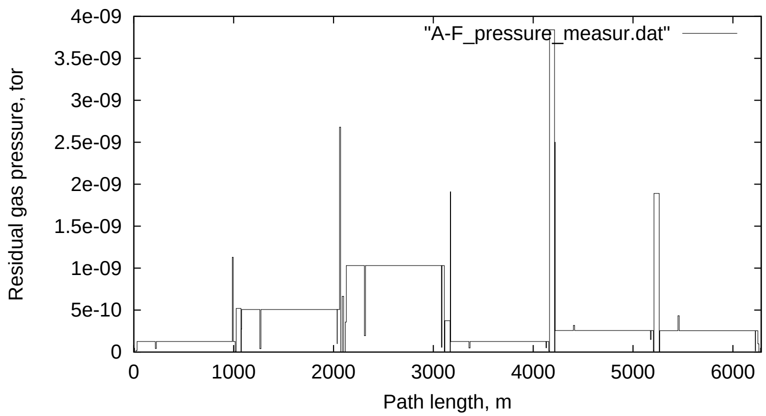
Collimator	β-function (m)		Dispersion (m)	Phase advance between primary and secondary collimators (deg)	
	horizontal	vertical		horizontal	vertical
D49 primary (p)	84.8	74.1	1.8	0	0
E03 secondary (p)	96.3	58.6	2.4	45	41
F172 secondary (p)	88.0	36.8	5.6	340	344
F173 primary ($\overline{p}$)	61.5	50.0	4.9	0	0
F171 secondary ($\overline{p}$)	94.8	34.1	5.8	7	12
E02 secondary ($\overline{p}$)	93.3	59.0	2.3	300	313

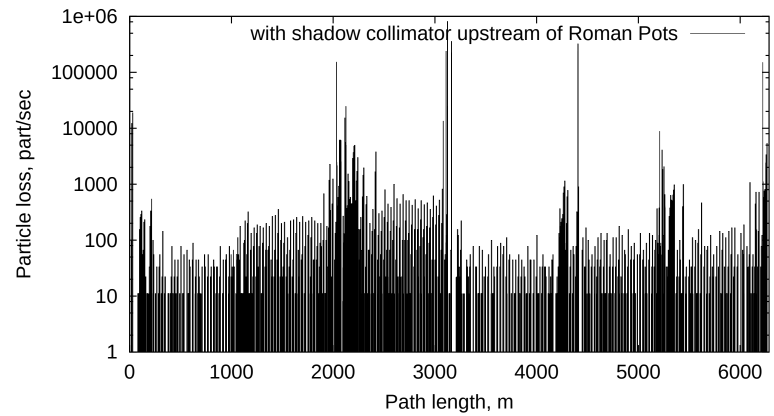
TEVATRON RUN II (5)



The 5-σ proton (red) and antiproton (green) spatial distributions (STRUCT). *Left:* at proton primary collimator D49 (top) and secondary collimators E03 (middle) and F172 (bottom). *Right:* at antiproton primary collimator F173 (top) and secondary collimators F171 (middle) and E02 (bottom).

BEAM-GAS SCATTERING IN TEVATRON





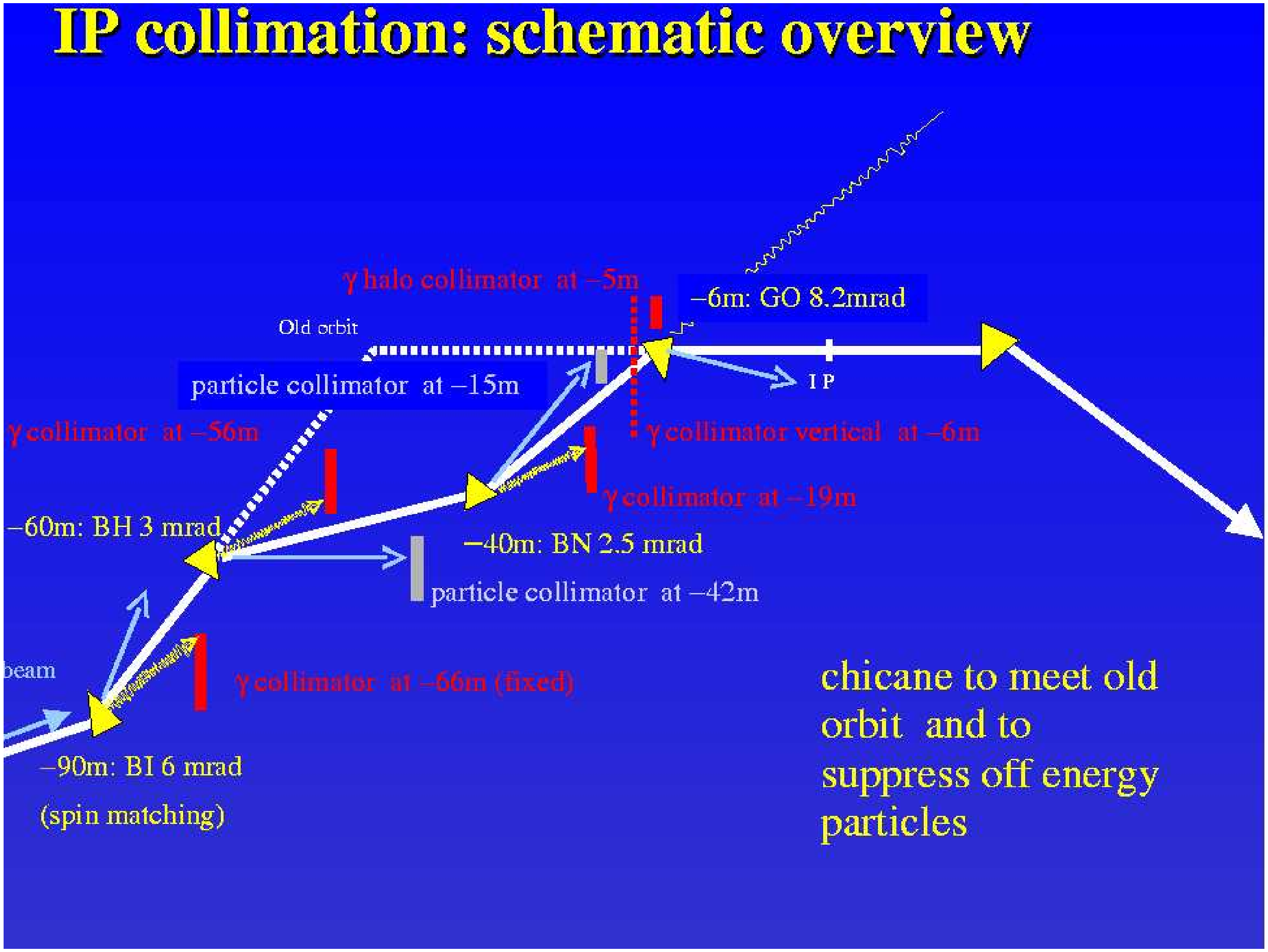
Measured residual gas pressure (*left*) and STRUCT-calculated beam loss distribution in from nuclear elastic beam-gas scattering (*right*).

10-FOLD INCREASE OF COLLIMATION EFFICIENCY BY USING A BENT CRYSTAL AS A PRIMARY COLLIMATOR

Table 1: Halo hit rates at the Fermilab DØ and CDF Roman pots and nuclear interaction rates N in target and crystal (in $10^4 p/s$)

	With target	With crystal		
		Amorphous layer thickness		
		10 μm	5 μm	2 μm
DØ	11.5	1.35	1.60	1.15
CDF	43.6	5.40	3.20	3.43
N	270	82.4	70.6	50.3

HERA (1)


IP collimation: schematic overview
γ halo collimator at −5m
−6m: GO 8.2mrad
Old orbit
particle collimator at −15m
I P
γ collimator at −56m
γ collimator vertical at −6m
γ collimator at −19m
−60m: BH 3 mrad
−40m: BN 2.5 mrad
particle collimator at −42m
beam
γ collimator at −66m (fixed)
−90m: BI 6 mrad
(spin matching)
chicane to meet old orbit and to suppress off energy particles

HERA (2)

Experimental Backgrounds

There are four sources of backgrounds, all of which have been explored with experiments. The results are in reasonably good agreement with simulations performed by H1 & ZEUS

- direct synchrotron radiation: tolerable after tuning
- direct leptons

  noticeable contribution for e+ only runs, collimators not very effective for e+
- backscattered synchrotron radiation

  bad in case of ZEUS shielding needs to be redesigned
- direct proton background

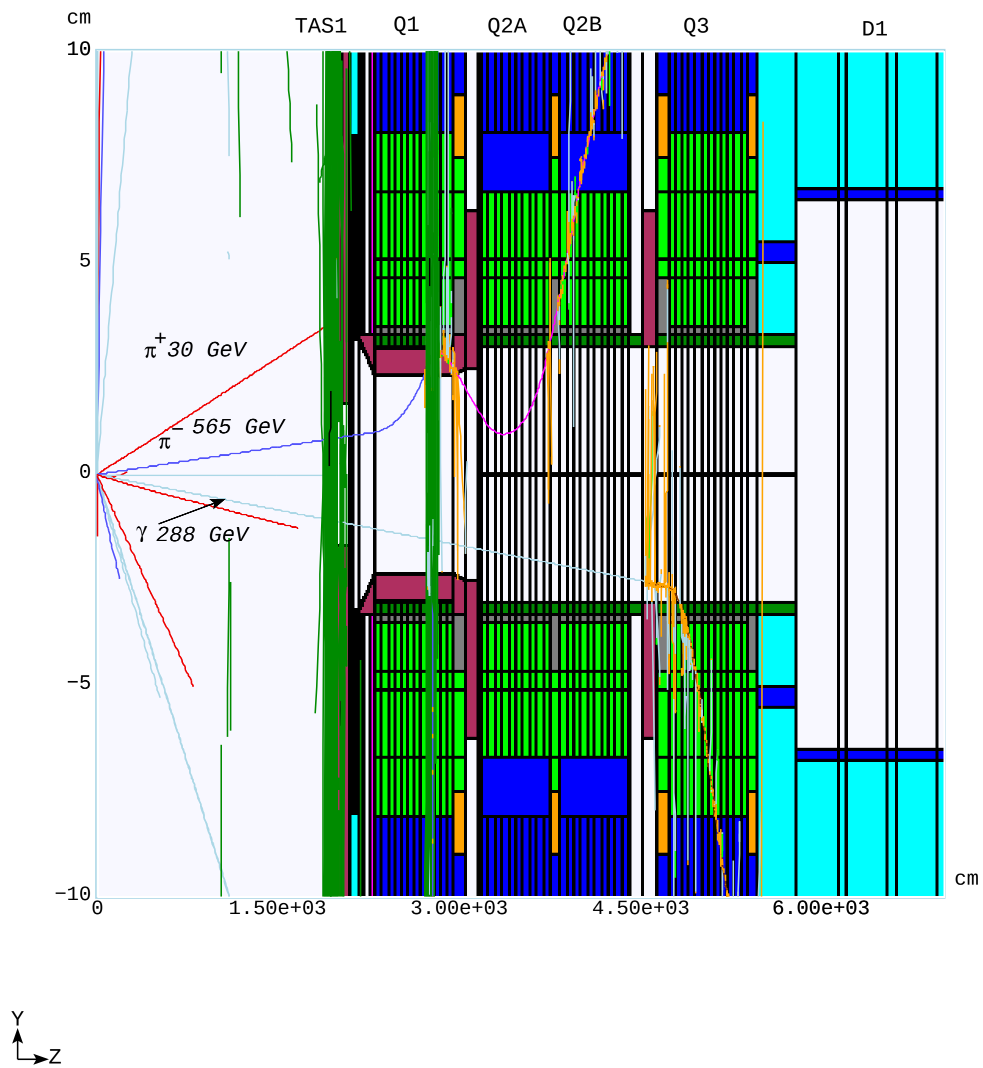
  beam gas scattering close to IP, related to vacuum, correlation with cold surface unclear

HERA (3)

Work coordinated by ZEUS and H1 involving an "overdesigned" mask (named C5). – Courtesy of Michiko Minty (DESY).

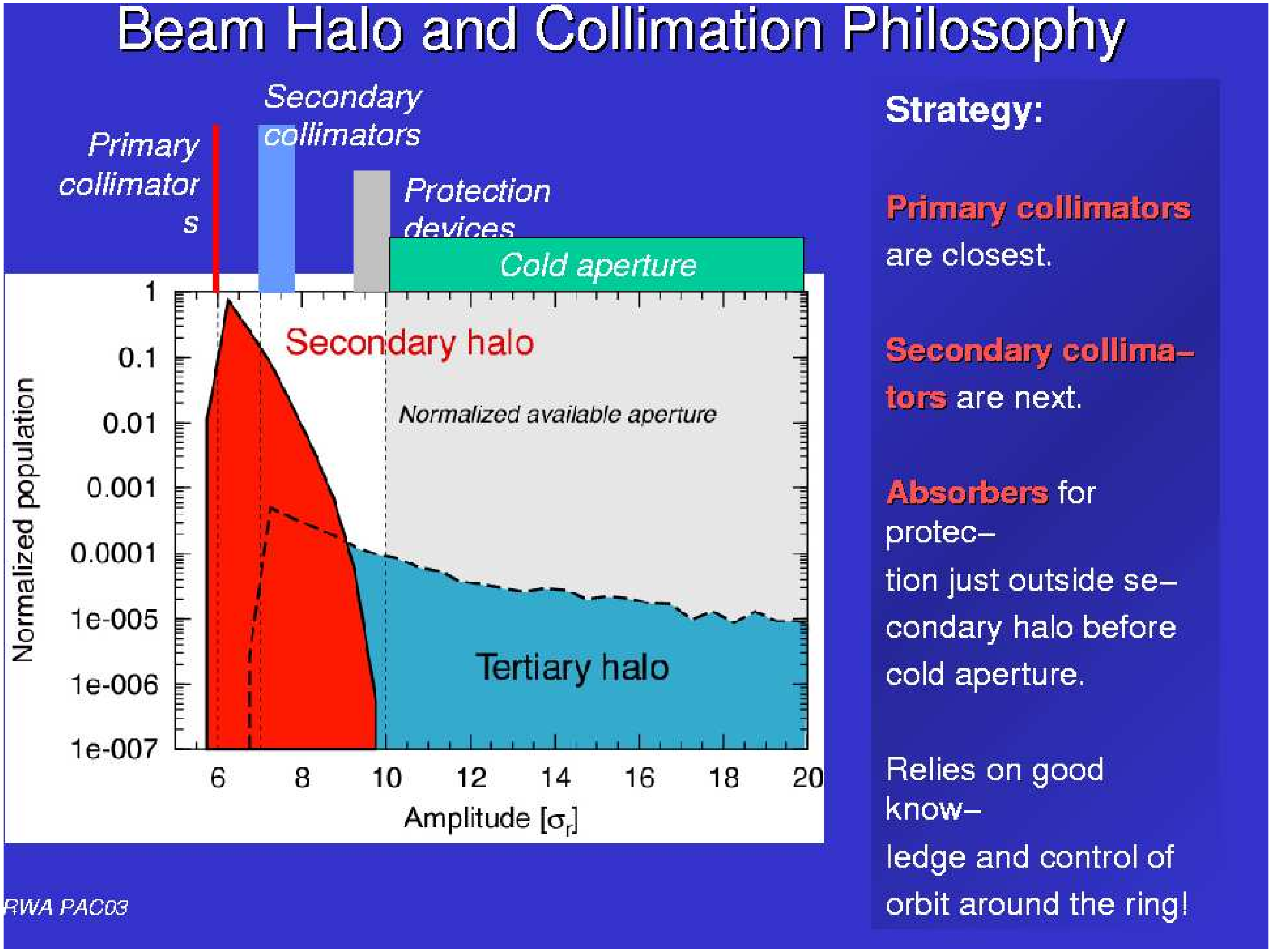
The mask's main purpose is to shield from backscattered synchrotron radiation from the lepton beam. However, it is also a scattering source for protons. So, it will be made **thinner**. Reconstruction of the IP location revealed many events coming from this mask located about 0.8 m downstream (as seen by the lepton beam) of the IP. Also of interest regarding this mask: a sample of the material was heated under vacuum in a test environment. A residual gas analysis revealed Zinc! Of course, this is bad for a vacuum system as it isn't well pumped. The C5's have been removed and analyzed from both IPs and it is found that the sample from the ZEUS experiment is Zinc-free, while that at H1 is not. The new C5's have both tested to be Zinc-free. How the Zinc came to be present is unclear (the mask is made of copper-coated Tungsten manufactured outside DESY, the coating procedure is proprietary, but the industry claims NOT to use Zinc).

LHC INTERACTION REGION IN MARS14



LHC IP1/5 PROTECTION SYSTEM

- The TAS front copper absorber at L=19.45 m (1.8 m long, 34-mm ID, 500-mm OD).
- A 7-mm thick stainless steel (SS) liner in Q1.
- The SS absorber TASB at L=45.05 m (1.2-m long, r=33.3-60 mm).
- A $\sim$3-mm thick SS liner in the Q2A through Q3.
- 40-cm long SS masks at L=23.45 m, r=250-325 mm to protect the Q1 slide bearings.
- The neutral particle 3.5-m copper absorber TAN at 140 m.
- The 1-m long TCL SS collimator at 191 m from IP.



Beam Halo and Collimation Philosophy
Primary collimators
Secondary collimators
Protection devices
Cold aperture
Secondary halo
Normalized available aperture
Tertiary halo
Normalized population
1
0.1
0.01
0.001
0.0001
1e-005
1e-006
1e-007
6
8
10
12
14
16
18
20
Amplitude [σ_r]
RWA PAC03
Strategy:
Primary collimators are closest.
Secondary collimators are next.
Absorbers for protection just outside secondary halo before cold aperture.
Relies on good knowledge and control of orbit around the ring!

Achievements…

System layout has been worked out and **provides required cleaning efficiency**.

Collimation has been **integrated** into machine optics and layout.

… and open questions

Foreseen collimator **materials do not withstand** the expected beam impact (~8 bunches out of 2808). Require factor 100–200 better resistance!

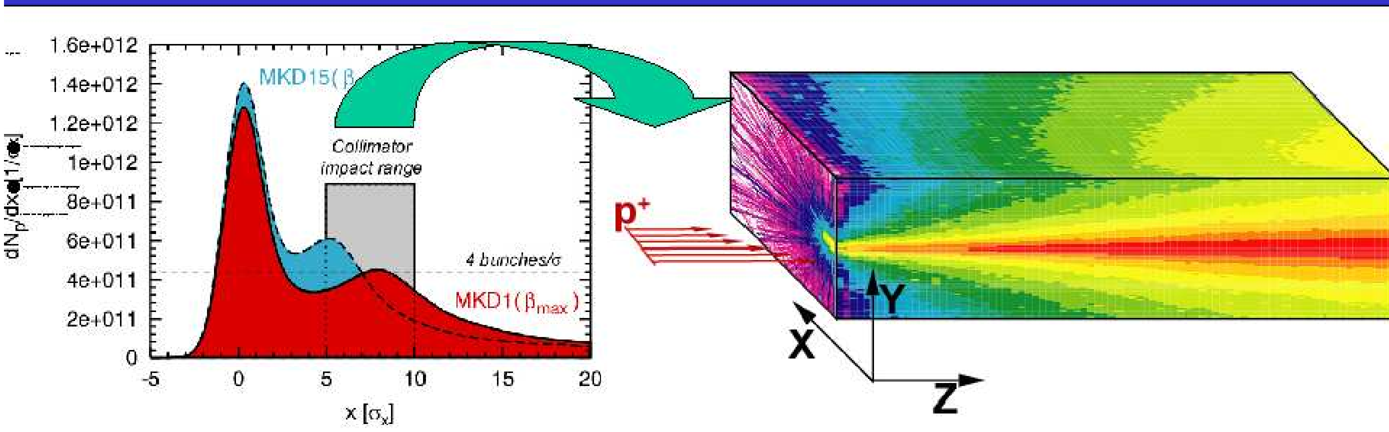
Impedance from collimators is **critical** (similar to the rest of the machine or larger).

High activation imposes severe restrictions for access. How to service the cleaning insertions?

RWA PAC03

Material Studies

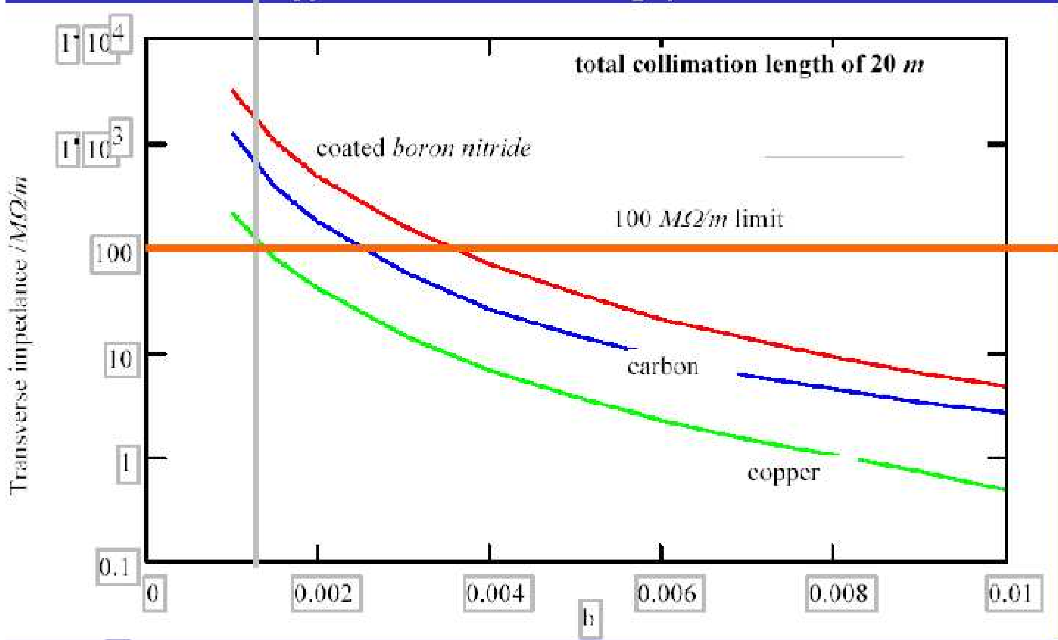
Irregular dump ...



RWA PAC03

Impedance Constraint

Typical collimator half gap at 7



LHC impedance without colli–mators

A doubling can be accepted at 7 TeV with full powering of octupoles

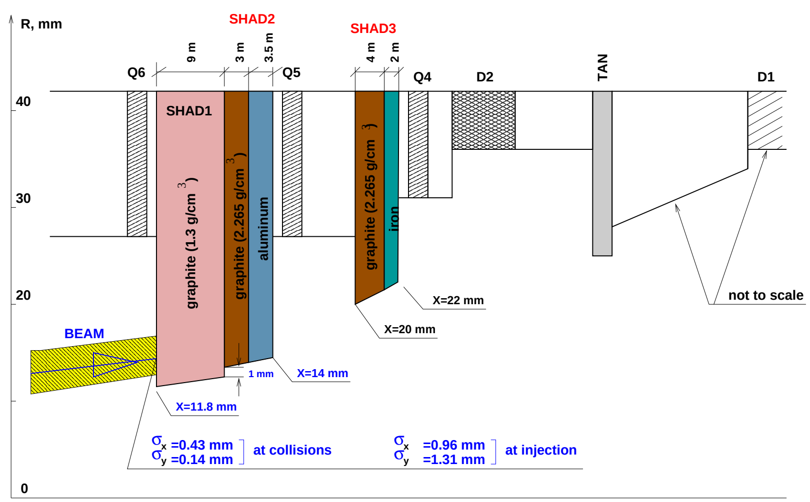
Half gap b [m]

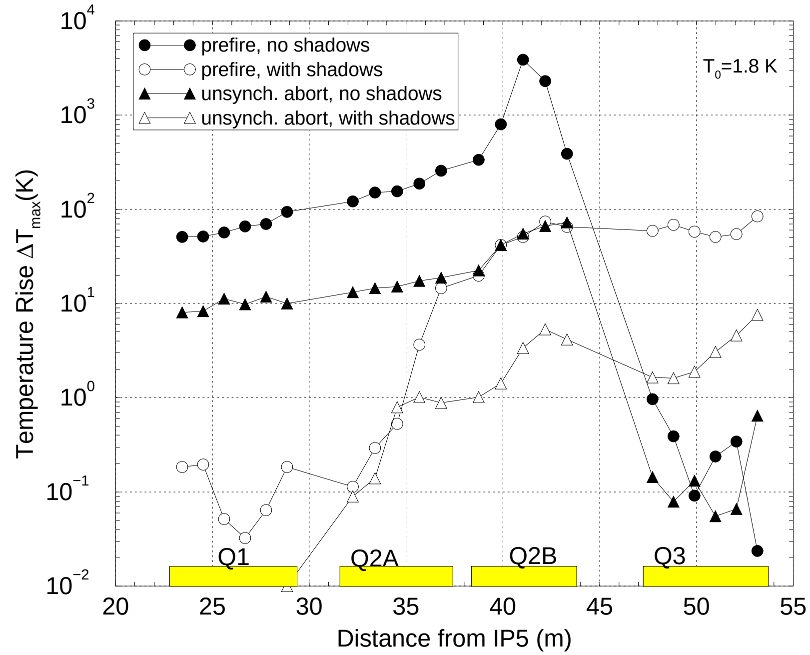
Graphite requires different collimation strategy (larger openings).

Not evident – possibilities under study (local triplet collimation, …).

RWA PAC03

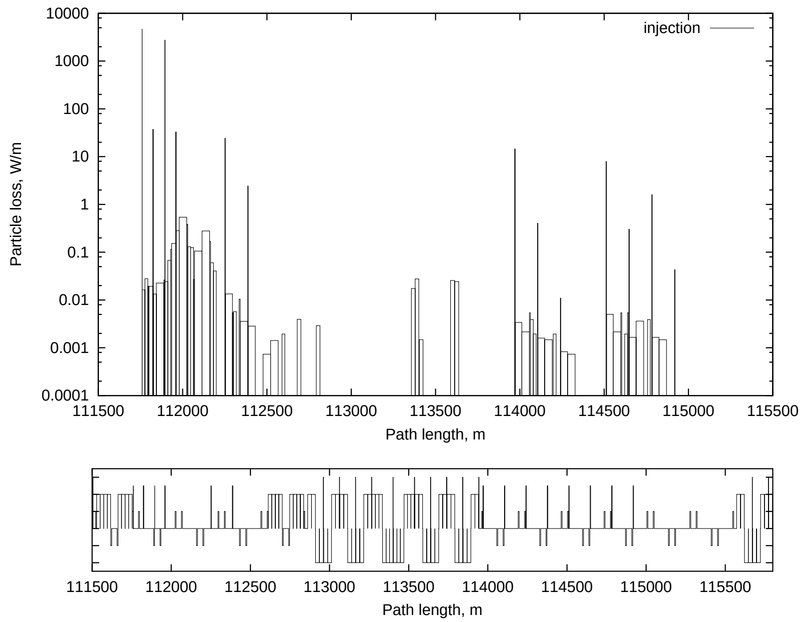
PROTECTION OF LHC IP1/5 AT BEAM ACCIDENT

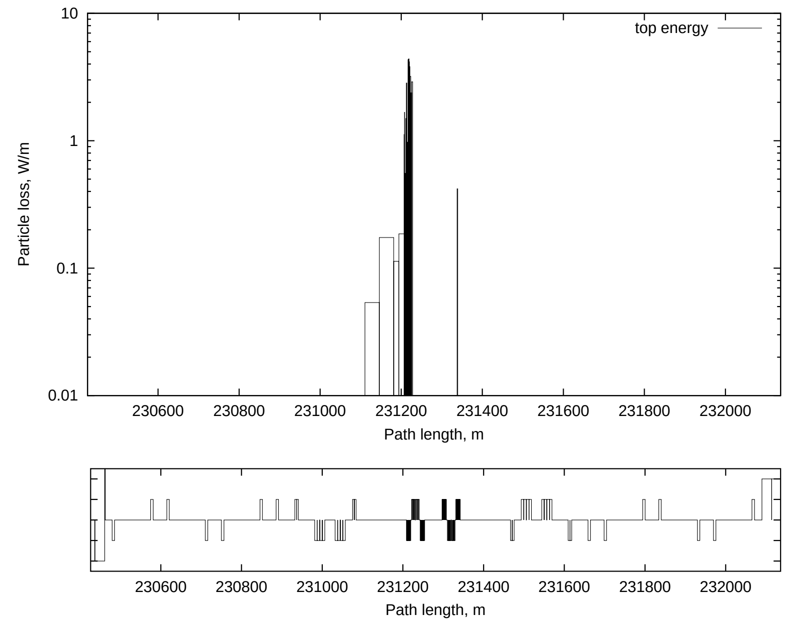




Shadow collimators in IP5 outer triplet (left) and MARS14-calculated peak temperature rise in IP5 inner triplet superconducting coils (right).

COLLIMATION AT VLHC





STRUCT-calculated beam loss distributions in the VLHC collimation section at injection (*left*) and interaction region at 20×20 TeV collisions (*right*).

SUMMARY

Beam collimation is mandatory at any superconducting hadron collider to protect components against excessive irradiation, minimize backgrounds in the experiments, maintain operational reliability over the life of the machine, and reduce the impact of radiation on environment. Only with a very efficient beam collimation system can one reduce uncontrolled beam losses in the machine to an allowable level both at normal operation and accidental situations. Two-stage collimation, proven to work at Tevatron, requires further R&D to improve efficiency at Tevatron and HERA, and meet LHC challenges – under realistic halo and beam loss scenarios and engineering constraints, and exploring novel techniques.